

**Multiscale Soil Moisture Variability from
Combined Remote Sensing, Modeling and Observations**
MTPE New Investigator Program Award NAGW-5240, NAG5-6395

James S. Famiglietti, PI
Department of Geological Sciences and Center for Space Research
University of Texas, Austin, TX

Report on Project Activity through February, 1998

1. Overview of Activities and Progress

Soil moisture stored near the land surface plays a central role in a wide variety of earth system processes, over a range of both spatial and temporal scales. In spite of its important role in earth interactions, little is known about spatial-temporal variations in soil moisture and the processes that control this variability. This is due in large part to the high frequencies at which soil moisture varies in space and time, and the associated difficulties in observing soil water at scales greater than the hillslope scale. Since many earth system processes are nonlinearly dependent upon soil moisture content, this variability must be better understood in order to fully understand the role of terrestrial soil water within the earth's climate system.

Given the near-term need to quantify soil moisture variations over a range of spatial scales, this project proposed a pragmatic approach whereby all available observations and reliable data products (e.g. in situ and field experimental observations, remote sensing, hydrological modeling), as they are required or available at a particular scale and location, are combined synergistically to produce "best possible" time series of soil moisture patterns at four distinct spatial scales: hillslope, catchment, regional and global. Original goals included continuing and extending hillslope studies at the Rattlesnake Hill field site in Austin, Texas; continuing and extending research on four dimensional data assimilation of remotely-sensed soil moisture into hydrological models at the catchment scale; and grid-based hydrological modeling of soil moisture and soil wetness at the regional and global scales. Soil moisture time series resulting from this research will support a range of studies in earth system science, including initialization/validation studies on regional and global hydrologic and climate system modeling; the scaling and parameterization of hydrological processes; and more generally, they should lead to an improved understanding of the role of soil moisture variability in meteorological and climatological processes.

Progress to date has been significant, while allowing for the exploitation of new and highly relevant opportunities that were not available at the time the original proposal was written (e.g. SGP97, GRACE). Hillslope work on Rattlesnake Hill has resulted in a new conceptual model for process controls on soil moisture variability at that scale. At the catchment scale, joint work with the University of Arizona (Shuttleworth and Houser) has demonstrated the feasibility of synthesizing distributed fields of soil moisture by the novel application of 4DDA into the TOPLATS spatially-distributed hydrological model using the Monsoon '90 data set. Global scale work has been initiated in which the feasibility of

extracting estimates of variations in terrestrial water storage from satellite observations of the time-variable gravity field is being explored.

A major focus of activities to date has been preparation for, and participation in, the Southern Great Plains 1997 (SGP97) Hydrology Experiment. In support of SGP97, the PI led in the planning and implementation of a multi-institutional field campaign to characterize soil moisture variability at the scale of remote sensing pixels (approximately 1 km² at SGP). The campaign was highly successful, and preliminary analyses are already yielding important and exciting results. To our knowledge, this campaign is the largest of its type ever attempted. Beyond contributing to the production and validation of soil moisture time series at various scales, these results should have major implications for understanding the accuracy of remotely-sensed soil moisture data and the variability that underlies remotely-sensed soil moisture products (i.e. the variance within 1 km² pixels). Results are described in detail below.

This project also includes significant educational and institutional support components. The details of progress in these areas can be found in the year 1 progress report and will not be discussed further here.

2. Summary of Progress to Date

Hillslope-scale studies. Near-daily gravimetric sampling (0-5 cm) along a 200 m downslope transect (9/95 through 9/96) at Rattlesnake Hill has yielded a new conceptual model for the processes that control variability along the transect. Specifically, results indicate that variability decreases with decreasing transect-mean moisture content as the hillslope dries down following rain events, and that the dominant influences on moisture content variability are dependent upon the moisture conditions on the hillslope. While topographic and soil attributes work continuously to move water downslope, correlations between topography and surface moisture content do not emerge until later in dry down sequences. Hence, under wet conditions, moisture content variability is most strongly correlated to variation in soil properties (e.g. porosity, hydraulic conductivity) while under dry conditions, soil moisture content in the 0-5 cm layer is most strongly related to topographic and soil attributes like relative elevation, aspect and clay content (see Figure 1.). Consequently, the dominant influence on soil moisture variability gradually changes from soil heterogeneity to joint topographic and soil control as the transect dries following significant rain events.

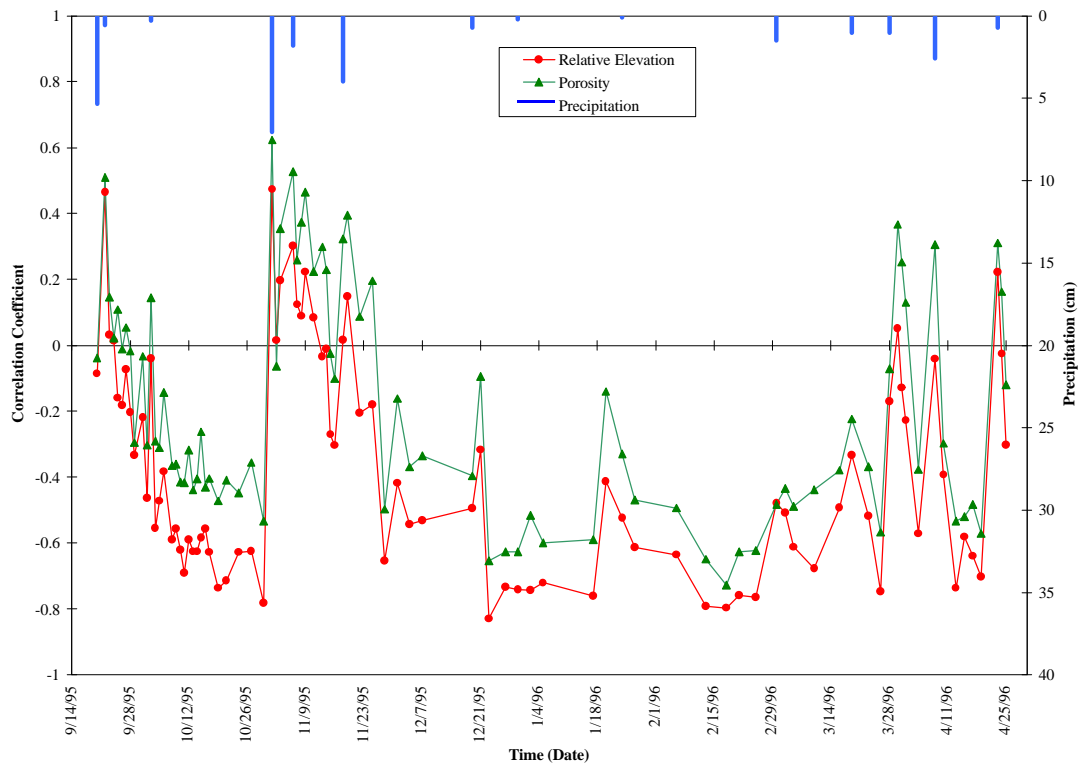


Figure 1. Time series of correlation coefficient of soil moisture with porosity and relative elevation. Note that positive correlation between soil moisture and relative elevation following storm events is due to covariance of porosity and relative elevation.

Other activities on Rattlesnake Hill during the past 20 months have included studies of temporal behavior of the variance of gravimetric moisture content measured at a point, and a preliminary investigation of the feasibility of hillslope-scale grid-based mapping using the gravimetric method.

Although the spatial scale of these studies is small, this research has implications for a range of issues in hydrology. First, a thorough understanding of hillslope-scale soil moisture variability will provide a foundation for better understanding hillslope hydrological, ecological and biogeochemical processes, many of which are nonlinearly related to soil moisture content. Second, since hillslopes are fundamental landscape units, this work will provide a basis for understanding soil moisture variations at larger scales. Consequently, this work will provide insight into the parameterization of soil moisture dynamics in larger scale hydrological models, and into the design of larger-scale soil moisture monitoring networks. Third, these studies will contribute towards an improved understanding of the representativeness of point soil moisture measurements as indicators of larger-scale average moisture conditions, and of the variability of soil moisture within larger-scale remote sensing footprints. In fact, results from Rattlesnake Hill led to the formation of several hypotheses, and impacted the design of the sampling network used to test those hypotheses, that were explored during our SGP97 campaign described below. Finally, it is worth noting that several topographic indices were better predictors of surface moisture content than the widely-used wetness index, including relative elevation, aspect and specific contributing area. The ease and accuracy with which relative elevation is

measured suggests that its utility as a predictor of surface moisture content outside of Rattlesnake Hill warrants further investigation.

The above activities have resulted in two Master's theses (James Rudnicki and Monika Bartelmann), two AGU presentations (Rudnicki and Famiglietti, 1996; Famiglietti et al., 1998), and one submitted manuscript (Famiglietti et al., 1998). Future local-scale activities will likely shift to either the University-owned Brackenridge Field Station or Pickle Research Campus. Planned activities are described in Section 3.

Catchment-scale studies. In collaboration with the University of Arizona (Shuttleworth and Houser) we have demonstrated the feasibility of synthesizing distributed fields of soil moisture by the novel application of 4DDA into a hydrological model. Specifically, a number of 4DDA methods were implemented into the PI's spatially-distributed TOPLATS model using the Monsoon '90 data set. Newtonian nudging procedures were shown to be preferable to other techniques because they preserve observed patterns within the sampled region while yielding plausible patterns in unmeasured regions (Houser et al., 1998). Activities in the past year were focused on completing the intercomparison of 4DDA methods and on preparing results for publication. While these activities are primarily funded by Water Cycle Processes Program project NAGW-4087, results from this work will have major implications for the research conducted under the present contract. Specifically, we hope to be able to transfer the methodologies developed under NAGW-4087 (and Arizona's NAGW-4165) to the larger, regional/continental scales (e.g. at SGP) and ultimately, global scales. (See the PI's NAGW-4087 progress report for a more detailed description of this activity and a complete list of papers/presentations resulting from this work.) In fact, current work involves implementing these approaches at the larger SGP site in a coupled mesoscale atmospheric/land surface model, and are described briefly in Section 3.

SGP97 (Local- to regional-scale studies). A major focus of activity to date has been directed towards the design, planning and implementation of a multi-institutional ground-based study of soil moisture variability, and preliminary analyses of the data collected. The driving force behind the study was the notion that significant soil moisture variability exists within remote-sensing footprints, and that this variability would not be quantified by the usual gravimetric moisture content sampling strategy that is typical of these experiments. Since many earth system processes are nonlinearly dependent on soil moisture, our belief is that this variability must be better understood to enable full utilization of the larger-scale remotely-sensed averages by the earth science community, particularly as the scale of these experiments, and the associated sensor footprint, increases in the future.

With these issues in mind, the PI took the lead on organizing an ambitious surface soil moisture sampling plan to complement the usual gravimetric sampling activities (in collaboration with Chip Laymon (MSFC), Tefari Tsegaye (Alabama A & M), Paul Houser (GSFC), Binayak Mohanty (USDA ARS Salinity Lab), and Tom Jackson (USDA ARS Hydrology Lab)). Overall goals of this ongoing study are to (a) characterize soil moisture variability at high spatial and temporal frequencies (i.e. near daily and within 1-km footprints); (b) understand the processes controlling this variability (e.g. precipitation, topography, soils, vegetation); and (c) determine how well this variability is represented in a time series of 1-km resolution remotely-sensed soil moisture maps. Specific tasks are to (a) quantify the spatial-temporal variability of surface moisture content (mean, variance,

distributional form, spatial pattern) in selected, representative quarter sections by means of supplementary sampling with a portable impedance probe soil moisture sampling device; (b) assess the accuracy of the remotely-sensed soil moisture maps by comparing ESTAR-derived mean moisture contents to those observed in the field; and (c) assess the representativeness of remotely-sensed maps of mean moisture content with respect to the underlying variance within quarter sections. First year activities were confined to planning and implementing the sampling strategy, and actual participation in the SGP97 experiment. Current activities are being devoted to analysis of the data, follow-up field activities, and the implementation of a 4DDA strategy to assimilate SGP maps of moisture content into a coupled mesoscale-atmospheric/land surface model.

After a lengthy planning process, sampling sites, the required equipment, and a sampling plan and protocol were identified. Six quarter sections were to be monitored daily (3 at the Little Washita, 2 at El Reno and 1 at the Central Facility; 49 samples/day on a 7 x 7 (100 m) grid) using portable impedance probes with a 6-cm sampling depth (Theta Probe, manufactured by Delta T) and DGPS for real-time navigation in the field. The plan was implemented at the beginning of the experiment, and routine sampling was conducted near-daily between June 19 and July 16, 1997. A comprehensive calibration effort was also initiated in Chickasha and is nearly completed. Participating institutions included the University of Texas (including 5 of the PI's graduate students: Marcia Branstetter, Johanna Devereaux, Steve Graham, Karen Mohr, and Matt Rodell), Texas A & M, Penn State, Boston University, Alabama A & M, M.I.T., Wageningen Agricultural University, the Institute of Hydrology, GSFC, MSFC, Princeton, the University of Maryland and others. In total, over 35 participants collected nearly 10,000 soil moisture measurements at the 6 sites. To our knowledge, this may be the largest ground-based study of soil moisture variability ever conducted.

Analyses have revealed a number of striking features. First, significant variability is present within remote sensing pixels, it exists at several natural and human-induced scales (i.e. variations are detectable at length scales consistent with topographic, soil, rainfall and agricultural practices (e.g. terracing/tilling)), and it is higher than that which has been previously reported in the literature. Second, variability is seen to increase with decreasing moisture content, and not decrease as suggested by several previous field studies, including those conducted within the Little Washita watershed in conjunction with past remote sensing soil moisture experiments (see Figure 2). Third, the form of the distribution is observed to change with time during a dry down, from normal, to gamma, to exponential. Previous research has only identified the distribution of surface soil moisture as normal. These early results are a clear indication that the supplementary surface soil moisture monitoring campaign was a success: past experiments have simply been too short in duration, and have not collected enough samples to accurately characterize soil moisture variability and its temporal dynamics. This field component of our SGP related research has resulted in several presentations (Devereaux et al., 1997; Devereaux and Famiglietti, 1998; Famiglietti, 1997; Famiglietti et al., 1998a,b) , one proceedings paper (Famiglietti et al., 1998) and two manuscripts in preparation (Devereaux and Famiglietti, 1998; Famiglietti et al, 1998), and will result in Devereaux's M. S. thesis.

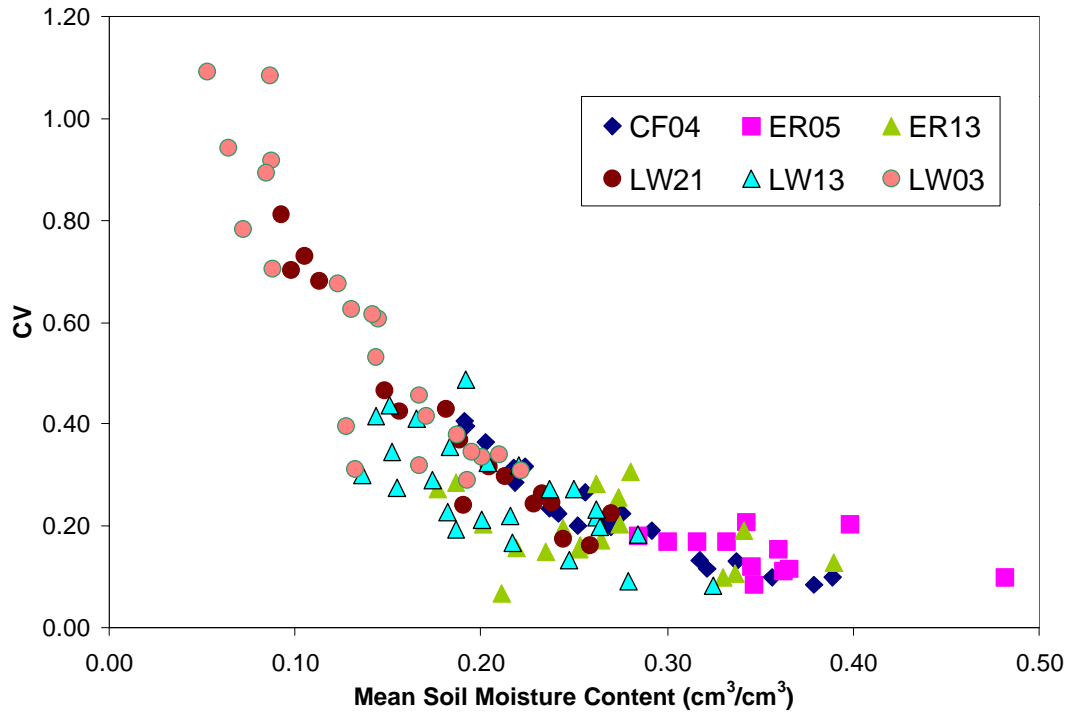


Figure 2. Coefficient of variation of moisture content vs mean moisture content for six sites in SGP97 region.

Results from this field study will have the following implications, all of which will be particularly important as the spatial scale of future missions and associated footprint areas increase. First, they will enable a more accurate assessment of the accuracy/uncertainty of the ESTAR-derived soil moisture maps. Second, they reveal the second and higher order sub-grid statistical information that remote sensing cannot provide. Third, they will provide generalized information on statistical moments as a function of moisture content that can be used to parameterize distributions of subgrid moisture content in hydrological and land surface models. Finally, when these data are combined with the rest of the SGP soil moisture data set, they will allow for the study of how the footprint-scale statistics scale up, with implications for the performance of larger-footprint soil moisture remote sensing and our ability to monitor and ground-truth soil moisture variability over larger areas.

Currently we are completing the first analyses and of these field data, preparing these results for publication, and initiating 4DDA research. Future work will continue the 4DDA studies and will address several of the topics outlined in the paragraph above. These topics will be discussed further in Section 3.

Global-scale studies. Since global-scale remote sensing of surface soil moisture is several years away, near-term alternatives must be sought to characterize the state of soil wetness over large, continental scale regions. A new and exciting initiative begun during the past few months involves an exploration of the feasibility of estimating variations in total water storage (soil moisture, groundwater, rivers, lakes, snow) from satellite

observations of the time-variable gravity field. A new, University of Texas satellite, the Gravity Recovery and Climate Experiment (GRACE, an Earth System Science Pathfinder satellite project directed by Byron Tapley) will monitor the time-dependent component of the Earth's gravity field with unprecedented accuracy, at two-week intervals beginning in 2001. Since the time dependent component of the gravity field depends primarily on mass variations of water in the atmosphere and on land, and in some regions on post-glacial rebound, subtracting atmospheric and post-glacial rebound effects should yield estimates of continental water storage variations. Preliminary work indicates that accuracies greater than 10 mm of water equivalent may be achieved at 500 km radial resolution (with accuracies increasing with increasing spatial scale and averaging times).

Current research is focused on determining the magnitude of water storage variations across the continents, and how these magnitudes vary with spatial and temporal averaging scales, with a view towards the utility of GRACE. Early model results using Global Soil Wetness Project (GSWP) results and NCEP/NCAR and ECMWF reanalysis products suggest that water storage variations are far greater than the GRACE detectability limits: these results are currently being prepared for presentation at the Spring AGU meeting (Rodell and Famiglietti, 1998a,b). Future research will concentrate on how to exploit GRACE-derived estimates of water storage variations by decomposing them into their component variations (e.g. snow, soil moisture, groundwater) using both modeled and measured hydrological data, and will be discussed briefly in Section 3.

GRACE-derived estimates of changes in continental water storage should provide an important, independent and observed (i.e. not modeled) source of data that can be used in a range of hydrological and climatological applications. These include initializing, constraining and validating the soil water components in GCMs (e.g. like that currently modeled by the GSWP); estimating changes in the total amount of water stored on land; estimating evapotranspiration from large regions (by providing the storage change term in the water balance equation); estimating rates of groundwater depletion; and estimating variations in the snow load, with implications for snowmelt prediction.

3. Planned Activities for the Remainder of the Project Duration

Hillslope-scale studies. The Rattlesnake Hill data set contains moisture content information at three soil levels (0-5 cm, 5-10 cm and 10-15 cm), yet only the upper 5 cm have been analyzed and published to date. Future work with the Rattlesnake Hill data will explore the variability in these deeper soil layers, the processes controlling this variability, and the relationship between the deeper soil moisture contents and those observed in the surface 5 cm.

Future local-scale activities will move from the Rattlesnake Hill site to the University of Texas Brackenridge Field Station or to the UT Pickle Research Campus. An important goal for future work is to begin baseline soil moisture monitoring using the Theta Probes purchased in support of the SGP campaign (including continuous measurements at various depths), as well as to install an array of soil moisture monitoring instruments similar to those found in the Little Washita Micronet and the Oklahoma Mesonet (e.g. the Campbell 229 Heat Dissipation Sensor and the Moisture Point TDR). In addition to providing

insight into the data yielded by the Micronet/Mesonet, the we will also be evaluating these sensors for potential recommendation to the proposed Texas Mesonet.

4DDA. A central focus of activity will be the implementation of the 4DDA scheme to integrate in situ and SGP-derived moisture content maps into a coupled version of MM5 and the PLACE land surface model over the SGP region. The coupled model as been obtained from Pete Wetzal at NASA/GSFC, and postdoc Wenje Hwu, a recent Arizona graduate, has recently joined our team to coordinate this activity. In addition to 4DDA, Dr. Hwu will also investigate issues of land-atmosphere interaction and its role in the formation of precipitation during the SGP campaign.

SGP97. Goals for the duration of the project include completing and publishing the detailed analysis of footprint-scale variability; comparing gravimetric and impedance probe soil moisture measurements to those derived by the ESTAR to quantify the accuracy of the remotely-sensed soil moisture maps; quantifying the “representativeness” of the ESTAR-derived soil moisture images with respect to the underlying variance observed in the field; and an analysis of how the footprint-scale statistics scale up to the area of larger footprints that may be associated with future, global soil moisture remote sensing missions, with implications for the performance of an ESTAR-type sensor at larger scales (e.g. under mixed pixel conditions), and the utility of sparse soil moisture networks (like that associated with the Oklahoma Mesonet) to monitor soil moisture variability over large areas. Corinna Prietzsch from ZALF, in Germany, will join the group from June 1998 to June 1999 to coordinate all but the first of these activities.

Global-scale studies. Beyond quantifying the spatial-temporal regimes under which GRACE-derived estimates of terrestrial water storage variations will be detectable, future work will focus on developing methods to translate these estimates into products that are useful to the hydrologic community. Activities will include: characterizing the contributions of changes in the individual components of continental water storage (soil water, groundwater, rivers, lakes, ice and snow) to total water storage changes and the time variable gravity signal using both global hydrological/climate models and field hydrologic observations (i.e. determining which components are detectable in which regions); determining whether characteristic component signatures can be identified from which a framework for decomposing GRACE-derived estimates of changes in continental water storage can be established; and identifying the spatial-temporal resolution of auxiliary hydrological measurements required to decompose GRACE-derived regional estimates of water storage variations into meaningful estimates of variations in its components. Doctoral student Matt Rodell will coordinate this project for his dissertation research.

4. Soil Moisture Research and Some Unresolved Science Questions

There are two broad categories in which I see a number of unresolved science issues that relate to soil moisture research and funding. The first is the spatial (horizontal *and* vertical) and temporal scales at which soil moisture plays a role in land-atmosphere interaction. I think that as a community we need to focus on *systematically* sorting these out, through both modeling and field experimental studies, with a view towards the design

of potential future regional/global soil moisture observing systems and the parameterization of hydrological processes in coupled models.

The second category is that of large-scale soil moisture remote sensing. Clearly, a strong understanding of the scaling of the footprint-scale statistics (or stated another way, the spatial-temporal soil moisture covariance field) is required before we can assess errors in any ground-based monitoring network or large-area remote observations. Sensor performance under mixed pixel conditions is another obvious, related and critical area of research for potential future large-footprint sensors (e.g. passive L-band). Intensive study of the SGP data set will surely yield insight here.

If it is unlikely that a passive L-band sensor will be included on a spaceborne platform, then a serious and concentrated effort should be devoted to exploring the potential of viable alternatives (C-band, active radar, GRACE) and/or the synergistic use of data from these satellites with hydrological or coupled land/atmosphere models to quantify large-area soil moisture variations.

5. Summary of Presentations and Papers Resulting from this Support

Papers

Devereaux, J. A. and J. S. Famiglietti, 1998, Calibration of Soil Moisture Impedance Probes for a Large Scale Field Experiment (SGP97), in preparation for submission to *Wat. Resour. Res.*

Famiglietti, J. S., J. A. Devereaux, C. Laymon, T. Tsegaye, P. R. Houser, T. J. Jackson, S. T. Graham, and M. Rodell "Ground-Based Investigation of Subgrid-Scale Spatial-Temporal Soil Moisture Variability During SGP97: Preliminary Analysis of Field Observations", *Proceedings of the International Workshop on Characterization and Measurement of Hydraulic Properties of Unsaturated Porous Media*, Riverside, CA.

Famiglietti, J. S., J. A. Devereaux, C. Laymon, T. Tsegaye, P. R. Houser, and T. Jackson, 1998, Ground-Based Investigation of Spatial-Temporal Soil Moisture Variability within Remote Sensing Pixels, in preparation for submission to *Wat. Resour. Res.*

Famiglietti, J. S., J. W. Rudnicki and M. Rodell, 1998, Variability in Surface Moisture Content Along a Hillslope Transect: Rattlesnake Hill, Texas, in review, *J. Hydrol.*

Houser, P. R., W. J. Shuttleworth, J. S. Famiglietti, H. Gupta, K. Syed and D. C. Goodrich, 1998, Integration of Soil Moisture Remote Sensing and Hydrologic Modeling Using Data Assimilation, conditionally accepted, *Wat. Resour. Res.*

Presentations

Devereaux, J. A. and J. S. Famiglietti, 1998, Soil Moisture Variability Within Six 1-km² Fields in Oklahoma, AGU Spring Meeting, Boston, MA, May 25-29.

Devereaux, J. A., J. S. Famiglietti, C. Laymon, T. Tsegaye, P. R. Houser, and T. Jackson, 1997, Correlation of Remotely-Sensed Soil Moisture Content with

- Gravimetric, Impedance Probe and In Situ Measurements, AGU Fall Meeting, San Francisco, CA, Dec. 8-12.
- Famiglietti, J. S., 1997. Ground-based Investigation of Spatial-Temporal Soil Moisture Variability in Support of SGP '97. International Workshop on Characterization and Measurement of the Hydraulic Properties of Unsaturated Porous Media, Riverside, CA, October 22-24, *invited paper*.
- Famiglietti, J. S., J. A. Devereaux, C. Laymon, T. Tsegaye, P. R. Houser, and T. Jackson, 1997, Ground-Based Investigation of Spatial-Temporal Soil Moisture Variability within Remote Sensing Pixels, AGU Fall Meeting, San Francisco, CA, Dec. 8-12.
- Famiglietti, J. S., J. A. Devereaux, C. Laymon, T. Tsegaye, P. R. Houser, and T. Jackson, 1998a, Impedance Probe Measurements of Surface Soil Moisture Variability Within Remote Sensing Footprints During SGP97, AGU Spring Meeting, Boston, MA, May 25-29.
- Famiglietti, J. S., T. J. Jackson, E. Burke, R. L. Elliott, G. Heathman, P. R. Houser, C. Laymon, J. Schneider, P. J. Starks, T. Tsegaye and P. J. van Oevelen, 1998b, Ground-Based Soil Moisture Data Collection Activities During SGP97, AGU Spring Meeting, Boston, MA, May 25-29.
- Famiglietti, J. S., M. Rodell and J. W. Rudnicki, 1998, Topographic and Soil Control of Variations in Surface Moisture Content Along a Hillslope Transect: Rattlesnake Hill, Texas, AGU Spring Meeting, Boston, MA, May 25-29.
- Rodell, M. and J. S. Famiglietti, Estimating Continental Water Storage Using Satellite Observations of Time-Variable Gravity, 1998, AGU Spring Meeting, Boston, MA, May 25-29.
- Rodell, M. and J. S. Famiglietti, 1998, An Assessment of the Detectability of Variations in Continental Water Storage by a Satellite Gravity Recovery Mission, AGU Spring Meeting, Boston, MA, May 25-29.

Theses and Dissertations

- Bartelmann, M., 1997. Mapping Soil Moisture Variability at Rattlesnake Hill, Texas. M. S. Thesis. The University of Texas at Austin, Department of Geological Sciences: Austin, Texas.
- Devereaux, J. A., 1998. Ground-Based Investigation of Soil Moisture Variability Within Remote Sensing Footprints, M.S. Thesis in preparation. The University of Texas at Austin, Department of Geological Sciences: Austin, Texas.
- Rundnicki, J. W., 1996. Hillslope-Scale Soil Moisture Variability: Rattlesnake Hill, Texas. M. S. Thesis. The University of Texas at Austin, Department of Geological Sciences: Austin, Texas.